The Long-Period seismicity before and during the volcanic crises: examples from two case studies

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Workshop on the Physics of volcanoes February 23-24, 2015

Long-Period (LP) seismic signals as detectors of the internal volcanic conditions

Long-Period (LP) events are seismic signals induced by the flowing of pressurized magmatic fluids through cavities in the volcanic rock whose source is normally modeled as gas pockets or slugs ascending along the conduit (Fig. A1). LPs are rich in low frequencies (<3Hz) and their waveforms are mostly independent of the case study, making them a universal signature of active volcanoes (Fig. A2). As they are produced by pressure inhomogeneities within the volcanic edifice, their occurrence is linked to the thermodynamic state of the bi-phase magma filling the shallow plumbing system. Indeed, before and during the volcanic crises, the LP process shows modifications as an effect of the changes of the internal state induced by magma dynamics.

Here we have defined a set of parameters to monitor the LP process: occurrence rate, variation coefficient (Cv, that is the ratio between standard deviation and mean value) of the inter-event time series, frequency content, energy and nucleation depth of the individual LP events. The LP events have been picked from the continuous seismic signal by a revised version of the Short-Term-Average/Long-Term-Average technique (Fig. A2, example from Shishaldin volcano, Alaska).

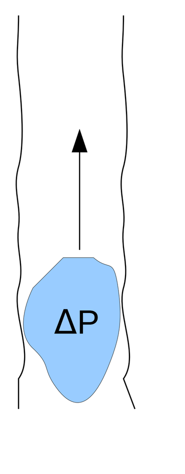

Fig. A1

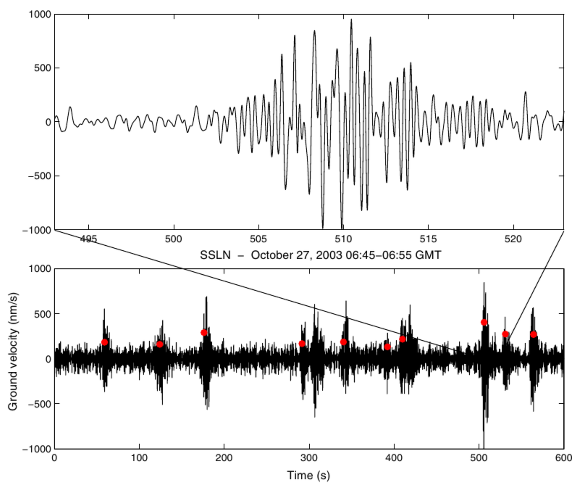

Fig. A2

Abstract

The Long-Period (LP) seismicity is common at active volcanoes and is usually modeled as due to pressurized magmatic fluids flowing through rock cavities. These signals are sensitive to the thermodynamic conditions of the magma-gas mixture in the shallow plumbing system and can thus be adopted as "detectors" of an impelling eruption. We found that at Stromboli (Italy) before and/or during recent volcanic crises the LP events can occur in swarms, which show different statistics, higher energy and shallower location than the stationary LP activity. We imputed the LP swarms to a quick depressurization ($|\Delta P| \geq 10^5$ Pa) of the shallowest (<0.8 km) part of the conduit. At Shishaldin (Alaska) the 2004 eruption is anticipated by a migration towards the surface of the LP source, which moves from ~8 km to ≲5 km below the crater rim. By simple assumptions, we modeled this source change as produced by an increase of the confining pressure within the plumbing system of ~5×10^7 Pa, possibly induced by an upward migration of ~10^8-10^{10} kg of magma.

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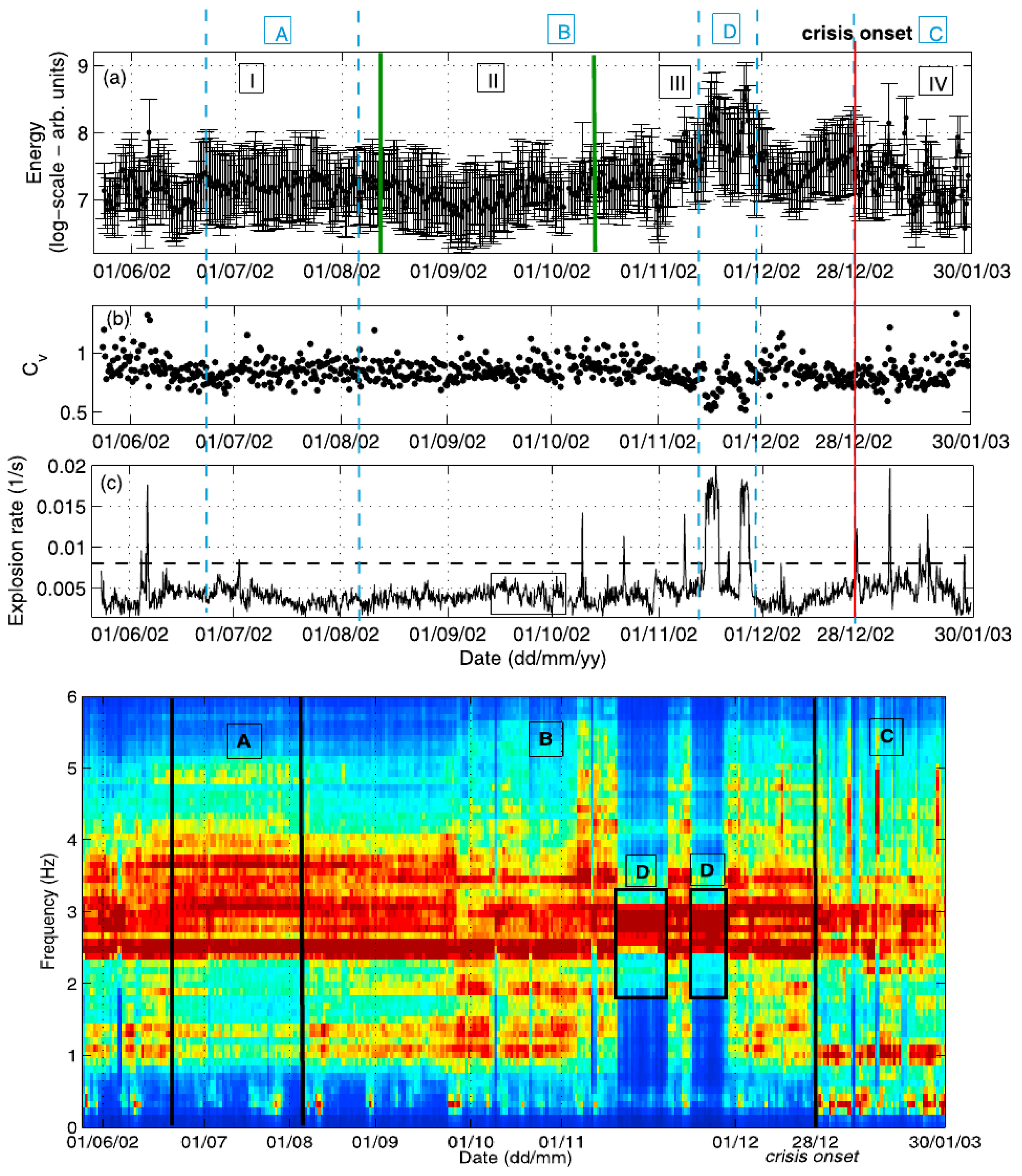
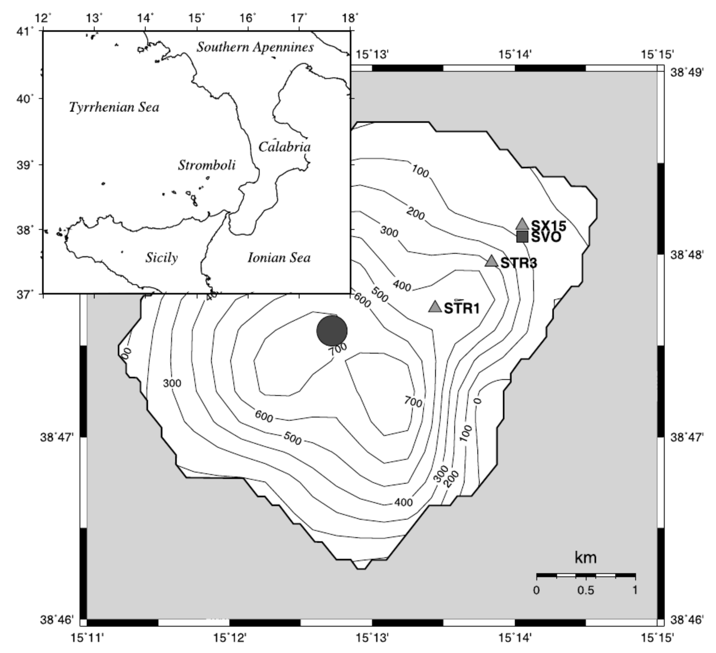
2. Stromboli (Italy)

2002-2003 eruption

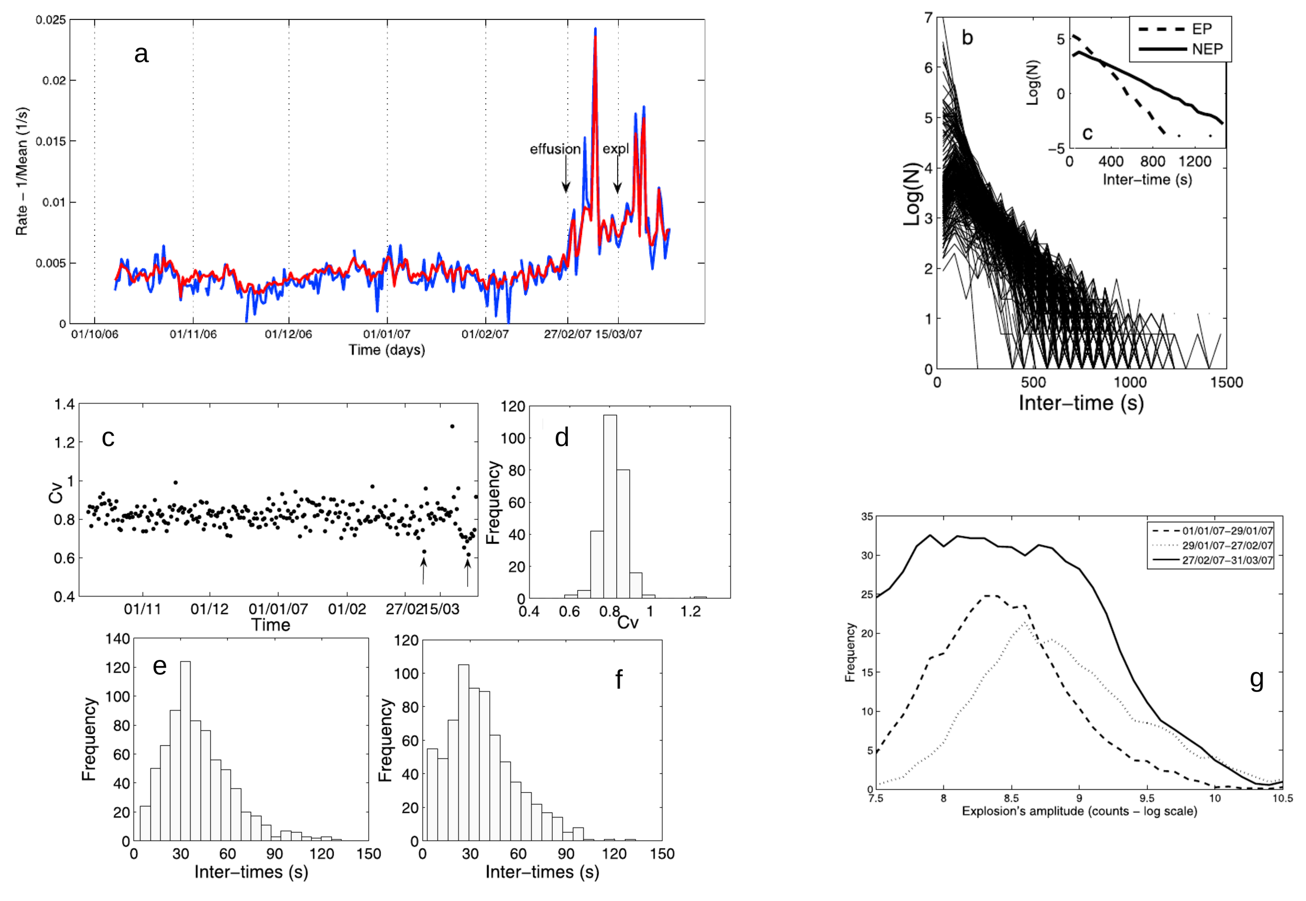


Progression of energy, Cv of the inter-event times, occurrence rate and spectra of the LP events picked at SX15 before and during the 2002-2003 eruption. No relevant changes are detected crossing the eruption onset, while two long-lasting LP swarms start about two months before the eruption. LP events during the swarms display higher energy and occurrence rate, quasi-monochromatic waveforms and lower variation coefficient, that means an almost constant inter-event time, whereas the standard LP activity is ruled by a Poisson process.

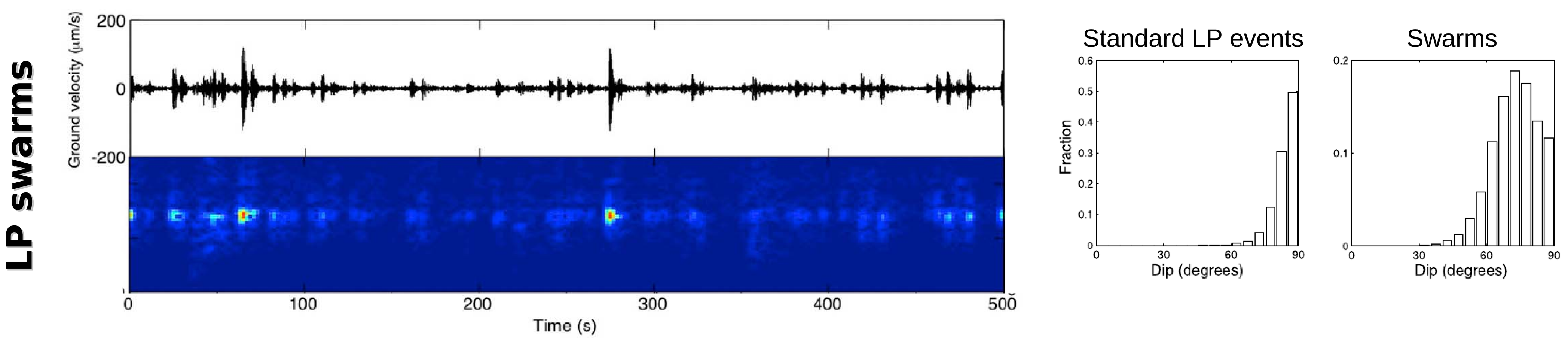


Stromboli displays a persistent low-energy explosive activity induced by gas slugs bursting at the free surface. The motion of the slugs towards the surface produces the LP seismicity. Sporadically major volcanic crises occur with both effusive and explosive phases. Here two recent cases are analysed: the eruptions of 2002-2003 (28/12/2002 – 06/2003) and of 2007 (27/02/2007 - 02/04/2007).

2007 eruption

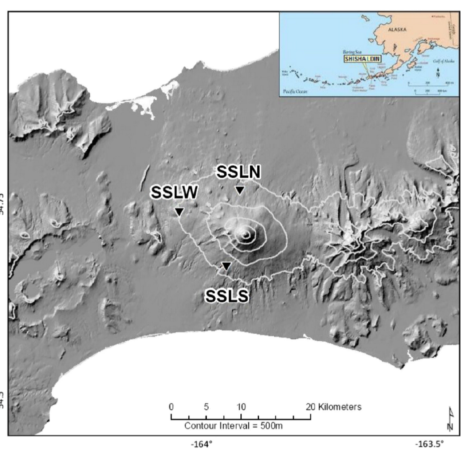


After the onset of the 2007 eruption the rate of LP events (detected at STR1) increases and three swarms occur (a). During both Eruptive Phase (EP) and Non-Eruptive Phase (NEP), the LP occurrence times are ruled by a Poisson process (inter-event times exponentially distributed and Cv~1 – b,c,d). During the swarms, the LP process becomes more periodic (e,f). During the Eruptive Phase the energy of the LP events is not log-normally distributed as in the stationary (NEP) activity (g).



A sample of recordings during an LP swarm and corresponding spectrogram (left). Together with a higher energy and occurrence rate than the standard LP activity and a more period point process, during the swarms the dilatometer (SVO) measures a negative strain rate indicating a pressure drop at the source of ~10^5 Pa. Moreover, the polarization dip angles point at depths of 0.3-0.8 km, mostly shallower than the source depths of the standard LP activity (~0.5-2 km) (right). The strombolian LP swarms can thus be considered an effect of a disequilibrium in the pressure field within the conduit and thus a proxy for non-equilibrium conditions in the shallow plumbing system.

Shishaldin (Alaska)



Shishaldin volcano is the second most frequently active of the Aleutians archipelago with nearly 40 eruptions in the last 250 years. After the significant sub-Plinian basaltic eruption of 1999, the volcano reactivated in 2004, reaching the strongest phase of a minor eruption in May. This eruption was accompanied by an intense LP activity that is here described.

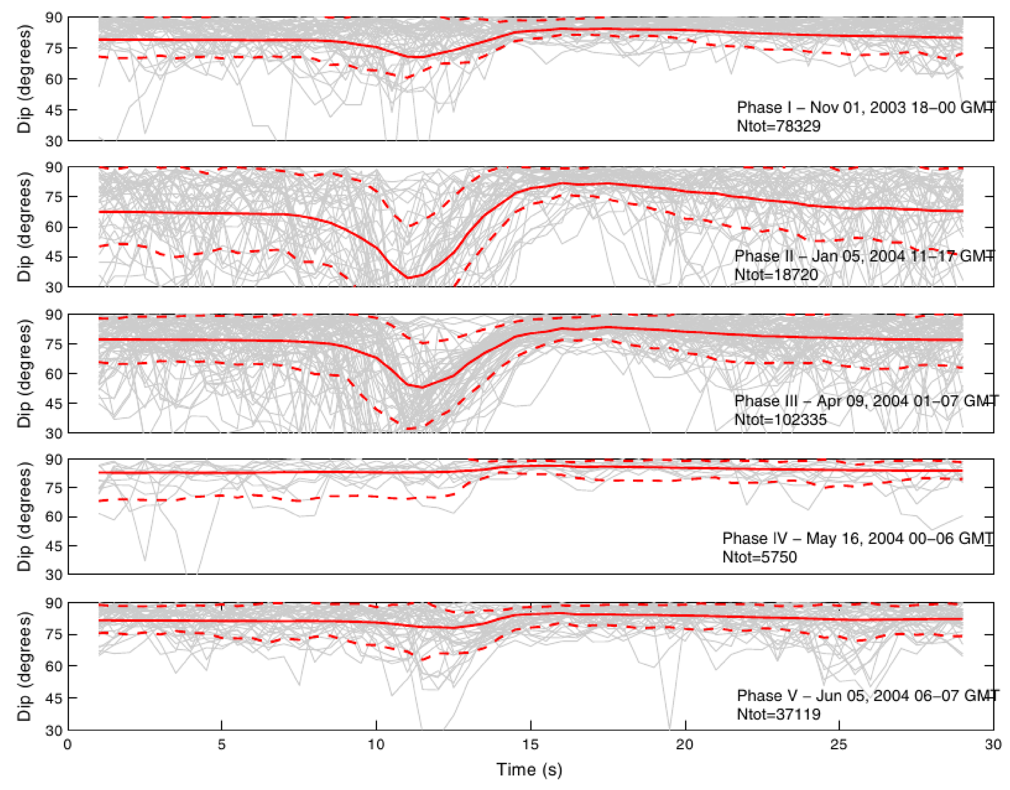


Fig. S2

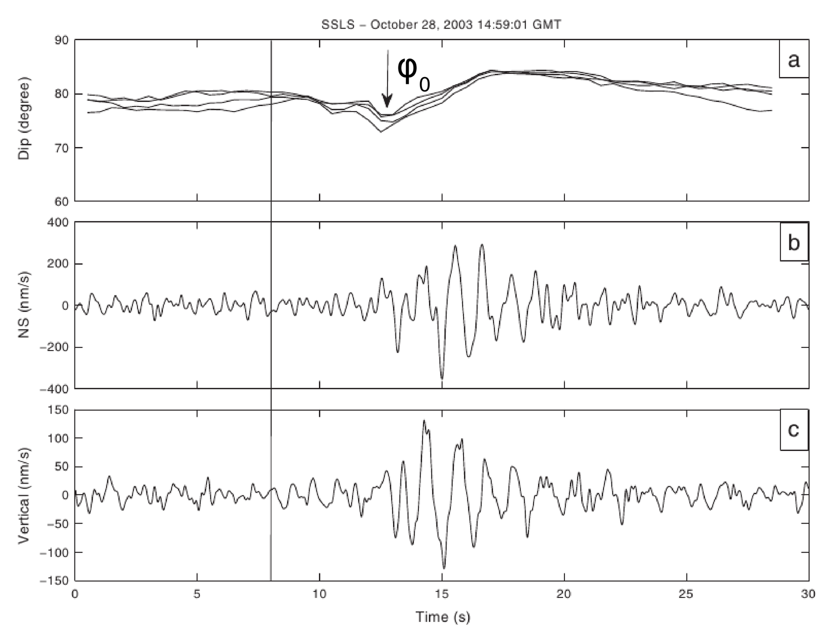


Fig. S1

The dip angle of the polarization vector shows a progression during the individual LP events moving from a lower value (φ_0) at the onset of the events towards shallower oscillations (S1). We defined φ_0 as the **nucleation dip**, that is the dip angle produced by the impulse of the nucleation of the gas aggregation generating the LP events. The nucleation dip is thus directly linked to the nucleation depth of the gas aggregations.

The nucleation dip is time-dependent and assumes a minimum in the Phase II (January 2004) and a maximum in the Phase IV (May 2004) (S2, S3c red line). It moves from about 40° at the end of Phase II to about 80° during the eruption (Phase IV), which means a shift towards the surface of the nucleation depth from ~6.3 km to ~3 km below SSLS. The dip angle of the background signal (S3c green line) mimics the nucleation dip, suggesting a contribution of the volcanic source. Similarly, the LP rate (S3a) and amplitude at SSLS (S3b red line) show an overall increase in the Phase III-IV, while the spectra appear rather stable along the phases (S3d).

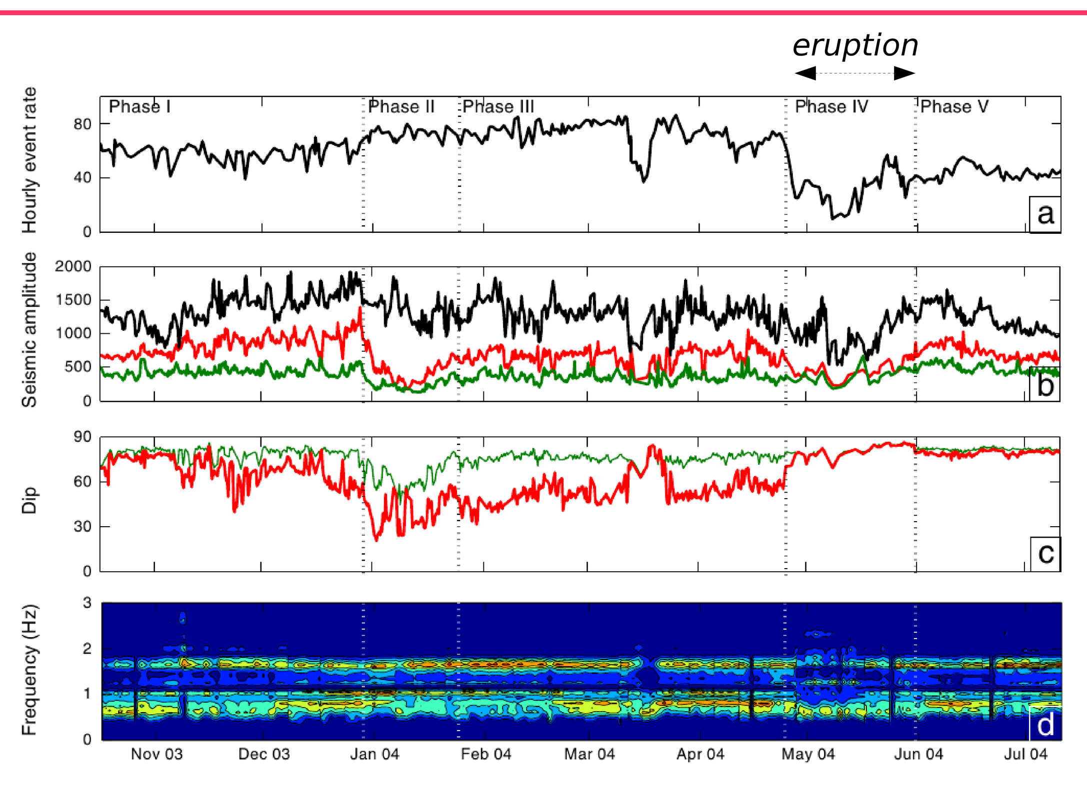


Fig. S3

LP migration responding to a pressure increase

We model the decrease of the nucleation depths before the eruption as due to an increase of the internal confining pressure, which would lead the gas aggregations to nucleate upper and upper in the conduit. In this framework, the change of hydrostatic pressure would equal the change of confining pressure:

$$\rho g \Delta h_{nucl\,depth} = \Delta P_{conf} \rightarrow \Delta P_{conf} \sim 5\times10^7\,Pa \qquad \frac{\Delta M}{M} = \frac{\Delta P_{conf}}{K}$$

$$\Delta M = 10^8 - 10^{10}\,kg \rightarrow \Delta V = 10^5 - 10^7\,m^3$$

$$using\ K = 10^6 - 10^8\,Pa,\ \rho = 1500\,kg/m^3$$

$$M = \pi R^2 l \rho,\ l \sim 3\,km,\ R \sim 6\,m$$